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The presence of COVID-19 face masks in the largest hypersaline lagoon of South America is predicted by urbanization level

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ABSTRACT

The inadequate disposal of face masks has caused a widespread presence of COVID-19 litter in the environment. We monitored 10 beach arcs along approximately 15 km of the largest hypersaline lagoon of South America looking for face masks during the lockdown (2021) and in the “new normal” (2022) period. Our working hypothesis is that the probability of finding face masks increases with higher urbanization levels, which was estimated by the Human Modification Metric. Approximately 3×10^{-3} face masks m^{-2} were found on nine of 10 beaches (90 %) during the lockdown. However, this reduced to 1×10^{-4} face masks m^{-2} found in eight beaches (80 %) after the lockdown. The probability of finding a face mask was significantly higher as urbanization increased ($z = 2.799$; $p = 0.005$). This situation imposes the need for a better waste management and environmental education actions, targeting the reduction of direct littering on coastal ecosystem.

The long-term persistence of plastic in aquatic systems is recognized as one of the most relevant environmental problem of the “Plasticene” era (Reed, 2015), impacting wildlife through ingestion, entanglement, entrapment, injuries and suffocation (Gall and Thompson, 2015). Also, plastic is a recognized vector for the introduction of non-indigenous algae, animals and pathogens, potentially amplifying the risk of bio-invasion and outbreak of wildlife diseases (Kiessling et al., 2015; Rech et al., 2016). Commonly, the amount of mismanaged litter in inland and coastal environments is predicted by surrounding urbanization and distance from rivers and streams, which thus should be targets of waste management actions (Dobaradaran et al., 2018; Schuyler et al., 2021; Serra-Gonçalves et al., 2019).

The World Health Organization (WHO) declared the novel coronavirus outbreak (COVID-19) on January 2020. Since then, a growing body of scientific evidences suggests that the pandemic is having mixed effects on the environment. Immediate positive effects include reduction of air and noise pollution (Bertucci et al., 2021; Yumin et al., 2021) and improved habitat quality for wildlife due the reduced human activities during the “anthropause” (Ben-Haddad et al., 2022; Costa et al., 2022; Gilby et al., 2021; LeClair et al., 2021; Manenti et al., 2020; Soto et al., 2021). However, the use of personal protective equipment (PPE) such as face masks to strengthen prevention against the spread of the virus had caused novel problems. Most of PPE is single-use, and the inadequate

disposal created an iconic problem related to waste management: the widespread presence of COVID-19 related litter in the environment (Ben-Haddad et al., 2021; Rakib et al., 2021). This is not surprising, since approximately 20 % of individuals usually recklessly throw away their disposable face masks (Selvaranjan et al., 2021).

A monthly use of almost 130 billion face masks is estimated globally (Prata et al., 2020). Considering improper disposal of just 1 % of disposable face masks by the world population, it would release to the environment ~ 10 million face masks (WWF International, 2020). This inevitably has led to interaction of animal life with this COVID-19 related litter with potential for short- and long term adverse effects (Hiemstra et al., 2021; Patrício et al., 2021). For instance, case studies have shown animals entangled in and ingesting face masks, and some birds using this PPE as nesting material (Hiemstra et al., 2021). COVID-19 related litter increases serious pressure on biodiversity already impacted by common plastic items, such as death related with digestive tract obstruction and starvation, due to restricted feeding activity after ingesting face masks and physical damages caused by entanglement (reviewed by Patrício et al., 2021). In addition to physical effects, PPE can act as vector for adsorbed heavy metals, persistent organic pollutants (POPs) and even for human-derived pathogens (Luksamijarulkul et al., 2014).

Beaches are typical sinks of disposable face masks, since the

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pollution level by PPE seems considerably higher than other places (Patrício et al., 2021). Lagoon beaches are even more exposed to chronic accumulation of face masks because of the limited water circulation. These assumptions led us to monitor 10 beaches along approximately 15 km of the largest hypersaline lagoon of South America looking for face masks during (2021) and after (2022) lockdown periods. Our working hypothesis is that the amount of face masks has decreased during the “new normal” period. In addition, we predict that the probability of finding a face mask increases with higher urbanization levels surrounding the beaches. This lagoon has calm hydrodynamic conditions, so we predict that circulation patterns are negligible as driver of face mask deposition on beaches, thus the pollution strongly depends on urbanization level as a proxy of direct littering.

A total of 10 beach arcs around the largest hypersaline lagoon of South America were inspected for finding face masks (~15 km) (Fig. 1). Araruama Lagoon (latitude 22°40'–22°57' S and longitude

42°00'–42°23' W) has a surface area of 220 km², an average depth of 2.5 m, extensive shallow areas with depths of 0.5–1.5 m, and occasional deep holes up to 17 m deep (Kjerfve et al., 1996). A number of small streams intermittently flow into the lagoon from the north (Kjerfve et al., 1996). The runoff from the main tributaries yields a mean discharge of $\sim 67 \times 103 \text{ m}^3 \text{ s}^{-1}$ (Kjerfve et al., 1996). A 14-km long narrow channel is the only connection to the sea and acts to limit tidal range between 0.8 and 1.3 m during spring tide (Kjerfve et al., 1996). This hypersaline lagoon is predominately crossed by densely populated urban areas and in numerous areas receives domestic sewage, but some preserved areas are still found (Kjerfve et al., 1996). Even with the increasing human pressure, the Araruama Lagoon still provides suitable habitats for many migratory and resident water bird species (Tavares and Siciliano, 2013).

To search for face masks on the 10 beach arcs (continuous sand stretch without barriers) of the Araruama Lagoon, the sand interface was inspected on September and October 2021 (during a lockdown period)

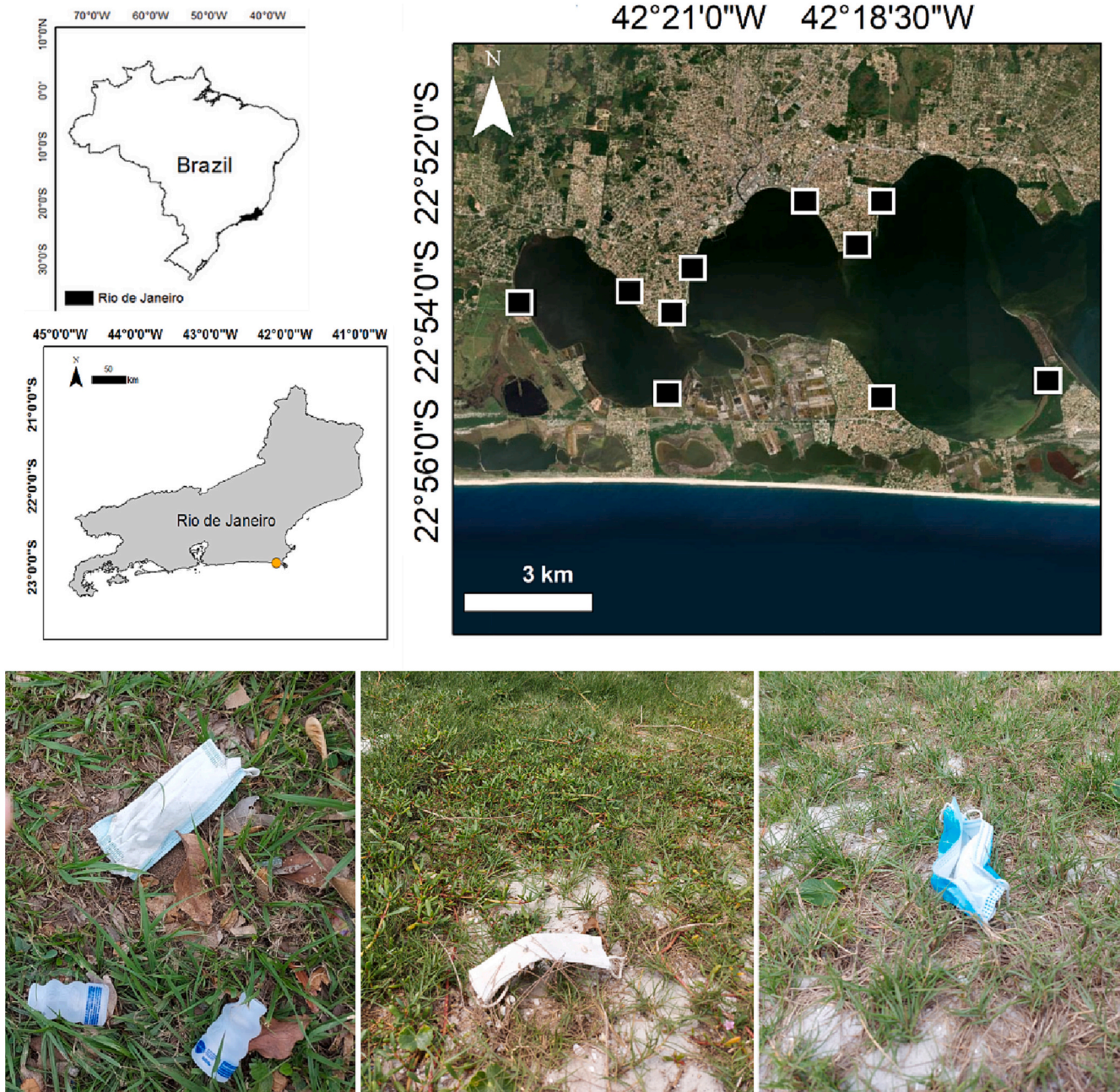


Fig. 1. Study site showing the Araruama Lagoon, Southeastern Brazil. Black squares are the beach arcs where face masks were searched for.

and in October 2022 (after the lockdown) during the morning (between 07:00 and 12:00). Beach width (W) and length (L) were determined through the ruler tool of Google Earth to determine beach area ($W \times L$) and to enable the calculation of face mask density (face masks per m^{-2}).

Location of each face mask was geo-coordinated with GPSMAP Garmim (62sc) with at least 5 m accuracy. For each face mask record, a random point was drawn along the entire sampling area. One hundred

locations were firstly distributed over the 10 beach arcs using the Google Earth tool and then, 50 background points from this pool were drawn to represent the “random points” (0) used in the presence-absence design. Geo-coordinates of face masks were used to determine the nearest distance to effluents (streams discharging into the lagoon) using the ruler tool in the Google Earth software (30 October 2022), and the urbanization level.

Table 1
Studies reporting mean face mask densities on beaches.

Ecosystem	Face mask density (masks m^2)	Year	Country	Method	Spatial coverage	Temporal coverage	Reference
Ocean sandy beach	1.4×10^{-2}	2021	Philippines	Unmanned Aerial Vehicle (three photos at 50 m intervals with resolution of 4160×3632 pixel)	One site ($283.2 m^{-2}$)	Snapshot	Abreo and Kobayashi (2021)
Ocean sandy and rocky beaches	3.6×10^{-2}	2020	Iran	Visual inspection in transects covering the entire beach width	Nine sites ($43,577 m^{-2}$)	Four times in 40 days with interval times of 1, 10, and 40 days after the first sampling	Akhbarizadeh et al. (2021)
Ocean sandy and rocky beaches	5.6×10^{-5}	2020	Peru	Visual inspection in transects covering the entire beach width	Eleven sites ($110,757 m^{-2}$)	Twelve consecutive weeks (starting in September)	De-la-Torre et al. (2021)
Ocean sandy beaches	6.1×10^{-3}	2020 and 2021	Bangladesh	Visual inspection in transects covering the entire beach width	Thirteen sites ($454,600 m^{-2}$)	Weekly during 12 consecutive weeks (November to January)	Rakib et al. (2021)
Ocean sandy and rocky beaches	1.1×10^{-5}	2021	Morocco	Visual inspection in transects covering the entire beach width	Eleven sites ($282,374 m^{-2}$)	Four consecutive months (before and after lockdown)	Ben-Haddad et al. (2021)
Ocean sandy beaches	6.0×10^{-3}	2020	Chile	Citizen Science - Visual inspection in $3 \times 3 m$ quadrats (6 to 22 sampling units depending on beach width)	Twenty two sites	Snapshot	Thiel et al. (2021)
Lake beaches (muddy and rocky substrate)	1.4×10^{-4}	2021	Ethiopia	Visual inspection in transects covering the entire beach width	Nine sites ($119,859 m^{-2}$)	Twelve consecutive weeks (first of April to the end of June)	Aragaw et al. (2022)
Ocean sandy beaches	6.2×10^{-4}	2021	Peru	Visual inspection in transects covering the entire beach width	Thirty-six sites ($1,179,727 m^{-2}$)	Snapshot (March to July)	De-la-Torre et al. (2022)
Ocean sandy beaches	3.5×10^{-4}	2021	Argentina	Visual inspection in transects covering the entire beach width	Fifteen sites ($769,655 m^{-2}$)	Snapshot (March to July)	De-la-Torre et al. (2022)
Wetlands, coastal and marine, jungle forest, Andean mountains, and Lomas	1.1×10^{-3}	2021	Peru	Visual inspection in touristic trails inside Protected Areas	Six sites	Snapshot (One site per day)	Dioses-Salinas et al. (2022)
Embayed sandy beaches	1.1×10^{-3}	2021 and 2022	India	Visual inspection in transects covering the entire beach width	Six sites ($143,080 m^{-2}$)	Three months	Gunasekaran et al. (2022)
Embayed sandy and rocky beaches	9.7×10^{-5}	2021	Iran	Visual inspection in transects covering the entire beach width	Thirteen sites ($293,825 m^{-2}$)	Twelve consecutive weeks	Hatami et al. (2022)
Island, open gulf and semi-enclosed gulf beaches	2.7×10^{-3}	2021 and 2022	Greece	Citizen science - Visual inspection in transects covering the entire beach width	Fifty sites ($315,928 m^{-2}$)	Fifty-nine sampling campaigns between June and March	Kouvara et al. (2022)
Embayed sandy beaches	1.2×10^{-3}	2022	Morocco	Visual inspection in transects covering the entire beach width	Five sites ($17,789 m^{-2}$)	Sixteen sampling campaign between February and June	Mghili et al. (2022)
Embayed sandy beaches	6.7×10^{-5}	2021	Brazil	Visual inspection in transects covering the entire beach width	Thirteen sites	Two periods (June–July and November–December)	Ribeiro et al. (2022)
Ocean sandy beaches	7.8×10^{-3}	2021	Philippines	Visual inspection in transects covering the entire beach width	Thirty-one ($48,200 m^{-2}$)	Snapshot	Sajorne et al. (2022)
Ocean sandy beaches	3.9×10^{-3}	2022	India	Visual inspection in transects covering the entire beach width	Ten sites ($246,268 m^{-2}$)	May, June and July	Kannan et al. (2023)
Semi-enclosed gulf sandy and rocky beaches	1.86×10^{-4}	2022	Iran	Visual inspection in transects covering the entire beach width	Twelve sites ($351,463 m^{-2}$)	Ten weeks (March to May)	Mohamadi et al. (2023)
Lagoon sandy beaches	3.0×10^{-3}	2021 and 2022	Brazil	Visual inspection in transects covering the entire beach width and length	Tem sites ($17,311 m^{-2}$)	Two periods (before and after lockdown)	Present study

The urbanization level surrounding each face mask and random points was estimated by the HMc - Human Modification Metric (Kenedy et al., 2019) using the packages “raster” (Hijmans, 2020) and “rgdal” (Bivand et al., 2021) in R software (R Core Team, 2022). The HMc measures the degree of human modification across geo-coordinated lands calculated as the per pixel product (HMs) of the spatial extent and the expected intensity of impacts including human population density, build up areas, croplands, livestock, roads, mining, oil wells, wind turbines and night-time lights through satellite imagery (raster data with 1000 m resolution). The final HMc value is calculated as:

$$HMc = 1.00 - \prod_{s=1}^n (1 - (HMs))$$

This fuzzy sum is a function that assumes that the contribution of a given factor decreases as other stressors co-occur. The HMc is a continuous gradient of modification ranging from 0 to 1. The HMc has been shown to be closely related to the classification of the level of human disturbance on beaches at local scales following categorical descriptions provided by authors (Barboza et al., 2021).

Generalized linear models (GLMs) with binomial distribution were employed to test the hypothesis that the presence of face masks on the beaches of Araruama Lagoon is related to urbanization level. The face masks presence (1) and random points (0) were the response variables included in the GLMs, whilst “HMc” and “nearest distance from effluent” were tested as predictor variables. This analysis was performed in R-software (R Core Team, 2022).

During the lockdown, approximately 3×10^{-3} face masks m^{-2} were found on nine of 10 beach (90 %) arcs sampled in the Araruama Lagoon. This value is higher than the PPE densities estimated in oceanic beaches from Peru (6×10^{-5} PPE m^{-2}) and Morocco (1×10^{-5} PPE m^{-2}), where face masks comprise more than 90 % of PPE (Ben-Haddad et al., 2021; Rakib et al., 2021). This is surprising because even the most urbanized sectors of Araruama Lagoon are not large enough to receive many people (beach width between ~4 and 20 m) compared to typical oceanic beaches. However, this hypersaline lagoon is mostly urbanized and present low-energy hydrodynamics, allowing the long-term accumulation of face masks in the same areas where people littered them. Face mask density on the Araruama Lagoon fringe was even higher than on beaches surrounding low-energy water bodies (e.g., lakes and embayed beaches) (Mghili et al., 2022; Mohamadi et al., 2023; Ribeiro et al., 2022) (Table 1).

The average density of face masks found on Chilean ocean beaches was substantially higher (6×10^{-3} face masks m^{-2} , Table 1), but the sampling was performed when lockdown measures had been suddenly relaxed, resulting in more people enjoying tourist beaches (Thiel et al., 2021). The mean density of PPE was also exceptionally high in Bangladesh (6×10^{-3} PPE m^{-2}), probably because the sampled beaches are near a large river (Rakib et al., 2021). The runoff from the main tributaries for the Araruama Lagoon is considered negligible (Kjerfve et al., 1996), and this reflected in the fact that the distance from effluent was not a strong predictor of the occurrence of face masks on the beaches ($z = 0.081$; $p = 0.935$) (Table 2).

Among the face masks registered in Araruama Lagoon, 90 % were found in the most urbanized areas. Thus, the probability of finding a face mask was significantly higher as urbanization increased ($z = 2.666$; $p = 0.008$) (Table 2, Fig. 2). Almost all studies that quantified the amount of

PPE on sandy beaches have found higher density of face mask on recreational beaches than in areas predominated by surfing, fishing or none activities (Ben-Haddad et al., 2021; De-la-Torre et al., 2021; Thiel et al., 2021). Clearly, this is associated with the high influx of beachgoers compared to low-used beaches. After the lockdown, the face masks were three times less abundant (9×10^{-4} face masks m^{-2}), which is a further evidence that cleaning services was not efficient during the pandemic. This situation requires the instant supervision because of the environmental risks that the disposal of hazardous materials on coastal ecosystems poses.

As mentioned above, beaches in the Araruama Lagoon are not usually overcrowded, and physical activities on the boardwalks in urban areas are very likely the main source of face mask disposal. The current litter pollution, still including face masks, therefore, requires an extension of cleaning operations as a basic management action. However, the addition of more garbage cans along the beaches edge and educational signs that make people aware of environmental and health risks of disposing face masks in the environment is pivotal for an efficient waste management (Thiel et al., 2021).

At the economic point of view, the aesthetic landscape should be a priority quest regarding the propagation of PPE in the Araruama Lagoon, since this hypersaline lagoon plays an essential role in the local tourism economy (Bertucci et al., 2016). However, the widespread presence of COVID-19 related PPE is beyond the risk of deterrence of beachgoers (Krelling et al., 2017). The remarkable coexistence of PPE and wildlife in the Araruama Lagoon has countless environmental risks that should be target of specific management actions. Firstly, the negative effects of COVID-19 litter on animal life are obvious, similar to those that have been reported for decades (Gall and Thompson, 2015; Laist, 1987). Hiemstra et al. (2021) performed an overview of interaction between animal species and PPE worldwide and among ~28 interactions found in the scientific literature, 25 % involved birds manipulating, ingesting, entangling in or using face masks as nesting materials. Birds are very abundant in the Araruama Lagoon, specially synanthropic and migratory species (Tavares and Siciliano, 2013).

Face masks are potential biohazard materials. Kasloff et al. (2021) found that although reduced from a baseline, significant quantities of viable SARS-CoV-2 could be recovered from inoculated N-95 and N-100 face masks at 14 days. As SARS-CoV-2 can remain infectious on contaminated PPE for extended periods under environmental conditions, widespread presence of face masks on beaches poses uncertain risks for interspecific zoonotic transmission of SARS-CoV-2 or any respiratory viruses among beachgoers (Olival et al., 2020). In addition, multiple species of wild or domestic animals may also carry SARS-CoV-2 or its related viruses; there are evidences that SARS-CoV-2 has a wide host range (Zhou and Shi, 2021). Warm-blooded vertebrates such as birds have particularly favourable characteristics for asymptomatic shedding of viruses and generation of novel mutant, recombinant e reassortant RNA viruses (Chan et al., 2013).

Our dataset has relatively limited temporal coverage, but represents a unique context of PPE pollution of lagoon beaches. Limited hydrodynamic circulation favours the accumulation of face masks disposed in the sand, exposing fauna and visitors to chronic pollution, especially in urban areas. In fact, we found that the presence of face masks in the highest hypersaline lagoon of South America is closely related with urbanization, corroborating our hypothesis and suggesting that direct littering is the main source of PPE at local scale. Incorporation of adequate environmental education to raise awareness about risks of disposing unmanaged face masks in the environment is pivotal to ensure an integral protection of beachgoers and biodiversity. Face masks must be treated as hazardous medical waste, including the proper identification, collection, separation, storage and transportation as basic management actions. Beaches must be cleaned periodically, but additional management handlers like disinfection, personnel protection and training are also required, particularly for cleaners and trash collectors.

Table 2

Binomial Generalized Linear Models. Masks occurrence points and random points are response variables. Significant predictors are marked with an asterisk.

Mask	Estimate	Std. Error	z-value	p-value
(Intercept)	−4.107	1.623	−2.530	0.011*
Urbanization (HMc)	5.558	1.986	2.799	0.005*
Nearest distance to effluent	0.000	0.000	0.081	0.936

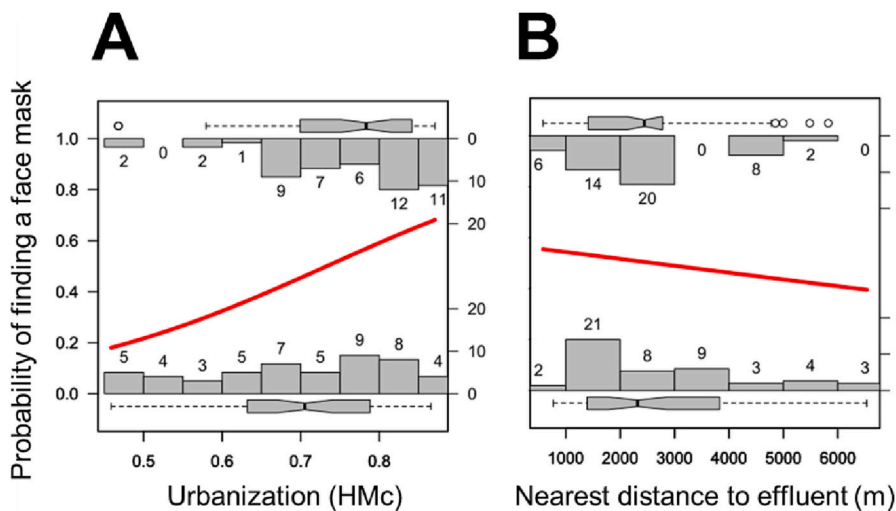


Fig. 2. Probability of finding a face mask according to urbanization level [Human Modification Metric by Kennedy et al., 2019] (A) and distance to effluent (B) (predictor variables) on beaches in the Araruama Lagoon, Southeastern Brazil. The line represents a Generalized Linear Model fitted with binomial distribution; the upper bars are the number of face masks and lower bars are the random points for each HMc intervals (x-axis); line inside boxes is median and boxes are interquartile intervals of the predictor variables in face mask points and random points.

CRedit authorship contribution statement

Leonardo Costa: Supervision; Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing.

Danilo Freitas Rangel: Conceptualization; Data curation; Investigation; Methodology; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing.

Ilana Zalmon: Validation; Visualization; Roles/Writing - original draft; Writing - review & editing.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

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